Non-Intrusive Sensors for Activity Analysis of Elderly People

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***Abstract*—In this paper, we describe on-going research conducted in our Laboratory concerning activity analysis of elderly or frail people with non-intrusive sensors. Activity is evaluated regarding autonomous mobility inferred from indoor tracking of many people. Non-intrusive photoelectric beam barrier sensors have been installed in our lab, in a nursing home and a medical care and research unit for respectively more than one year and 6 months. Incremental design, sensor fusion, data processing and acceptance concerns are discussed in the paper.**

I. Introduction

Motivations

Population ageing becomes a significant problem in our societies as it incurs both financial and social costs. Although human care and interaction for the frail and the elderly cannot be replaced by technological approaches and tools, at least for ethical reasons, these approaches may bring some relief to medical staffs and families. The general objective of our laboratory is to develop technological services for the care of frail and elderly persons.

Monitoring of human activities has extensively increased during the last years. It concerns a wide range of applications. For years, there are traditional areas such as crowd control, protection of high-value sites or personal sports activity tracking and coaching. More recently appeared new areas such as frail or elderly person monitoring.

For the first set of mentioned applications, the pursued goal is to obtain information as accurate and complete as possible on what is monitored. When monitoring elderly, sparse information with low accuracy may sometimes be sufficient for the targeted application and will probably be more simple to obtain. Because it is crucial to address the question of privacy, a fair balance between quantity and precision of the information yield by the monitoring system and the needs have to be sought. For example, it would not be appropriate for a monitoring system to yield information that allows inferring the detailed daily activity of a person when the need is only to check that this person has a minimal activity during the day.

In our research, we are focusing on monitoring indoor displacements of people in public area of buildings, with two complementary objectives

- to design a non-intrusive sensors and the best monitoring system to obtain a complete quantitative and/or qualitative information on the displacements of people,
- to investigate how much and what kind of interesting information on people activities - from a group and/or an individual point of view - we can infer from what we know of their displacements.

Related work

Sensors for healthcare have been used for years. In [1] a survey on wireless sensor networks with application to healthcare have been dressed till 2010. Many works have been carried out on Smart Homes as well, where sensors are central. Another comprehensive and thorough survey on this subject was done by Chan et al. in 2008 [2]. In 2013 Barath and Anithapriya presented a brief survey on health care for aged people based on sensor network [3]. Health care with sensor detection for an elder person is precisely our target application.

Authors of [4] demonstrate a proof-of-principle that night-time falls detection might be achieved using a low complexity and completely unobtrusive wireless sensor network in the home. Recently, researchers have made an enquiry to know the interest of people in senior fall prevention. Eighty-one percent (over 1900 respondents) "expressed an interest in sensor technology that can anticipate and prevent falls" [5].

In [6] authors used Passive Infra Red sensors (PIR) to count people in an office building to save energy. For tracking many people entering or exit the offices, they installed PIR sensors on both sides of each office door. This system is efficient to detect empty rooms.

In [7] an empirical study of human movement detection and identification using a set of PIR sensors is presented. The authors use an experimental design made of three PIR-based modules: one module on the ceiling and two modules on opposite walls facing each other. Their results taking advantage of machine learning algorithms for classification analysis are encouraging. They could achieve more than 92% accuracy in classifying the direction and speed of movement, the distance interval and identifying subjects.

Several technologies have been used for home monitoring. In particular the use of images and video analysis (see for example [8] where Sung and all use RGBD Images) may be appealing, but raises ethical concerns.

In [9] the authors also use sparse information that takes into account people intimacy. The information is collected from various sensors placed in the house and on mobile devices to infer probable activity of a supervised person. Nevertheless this work applies to the supervision of a single person.

Content and structure of the paper

In our experiments, monitored area is divided into several zones of interest separated by barriers. Our targeted result is the ability to count people in each zone, of monitoring the flows of displacements between several zones, and potentially of localizing some people or some group of people with a zone precision.

Commercially available infra-red barriers are not smart enough to fulfil our requirements - they report the event of crossing but do not address the direction of crossing. We have designed and developed a smart barrier that consists of a combination of non-intrusive sensors (infra-red barriers and PIR sensors) and that produces detailed information on nature, speed, and direction of crossing. This smart barrier, its design, and the quality of the results produced are presented in the first section of this paper.

The output of our experimental set-up are collections of dated events produced by such barriers. We also developed a simulator that produces similar collections of events for given scenarios of displacements of people. It gives us easily a big set of data for testing our algorithms for analysis of activities. The basic idea behind these algorithms is to sequentially consider the events in chronological order and to construct at each step a set of compatible displacement. Size of this set is increasing during the analysis because the consequence of an event may be defined equivocally - with probabilities attached to each possibility. To avoid combinatorial explosion, a global rating for each scenario is inferred from these probabilities, and only the best-rated ones are kept. External a priori knowledge on people behaviours can also be expressed as constraints allowing to filters the scenarios. Corresponding methods and implementations, as well as expectations and theoretical results, are discussed in the second section of this paper.

The third section presents two experimental set-ups that we have designed and developed. The first one is installed in a retirement home and the second one in a day care unit of a medical research center. In the retirement home, the area monitored is an aisle with several rooms and a couple of offices. People are patients, visitors, caregivers, doctors and technical staff. Our ultimate goal is to detect any possible change in the number of daily activities of one of the patients living there, with the assumption that activity is correlated with mobility. In the day care unit of the medical center, the area monitored consists of a lab zone, the day care zone itself, a waiting zone, and several facilities (information displays, toilets, coffee machines, ...) We aim to determine the flows of people between the zones, and average occupancy rates, namely the amount of exchanges between lab and day care zone, or average uses of the facilities. Data and expected results of the analysis are described and discussed as well in this third section.

Achievements and weak points of our work are summarized in the conclusion of the papers that introduces ongoing and future works.

II. Smart multi sensor barrier

Hardware specifications for the smart barrier was :

- based on commercially available low costs components,
- integrated in a minimal size 3D-printed shell,
- for use in a corridor of width between 1 and 3 meters.

Functional specifications was ability to detect single crossing, returning speed and direction, and to give as much as possible information on multiple quasi-simultaneous crossings, use of wheelchair or rollator.

Smart barrier design

Simplest solution consists of coupling together two commercially available infra-red barriers and to infers direction of crossing from the sign of the time delay between detections. Such barriers return a binary signal that changes when the beam is crossed, and changes again after a small delay.

Alternative was to use ultrasonic or infra-red distance sensors. They return an analog signal related to a distance measurement, the width of the corridor or a smaller value, when people is crossing.

Passive Infra Red sensors react to the temperature of the human body, in a well defined detection area - usually a cone. Some can be added to the solution to provide additional information.

In our lab, we have set up two test beds in two corridors of different widths, and experimented the previously described sensors systems in several situations corresponding to different values of the following parameters :

- direction of crossing
- speed of crossing (slow, normal, run)

and also in situations where two people are crossing almost simultaneously - in the same direction or not, with a small delay, a large one or not.

It turned out that coupled infra-red barriers were not able to detect multiple crossing because of their delay. Infra-red distance sensors provided more meaningful results but were quit difficult to calibrate. Sensors themselves are very sensitive to lightning exposure. Results produced by related signal processing is very sensitive to configuration parameters like the size of the sliding window in a moving average, or the threshold level.

Best results were obtained by a barrier composed of two infra-red distance sensors coupled with two directional passive infra red sensors, in the configuration shown on figure 1. Orientation of PIRs can be tuned mechanically onsite for calibration of the measurement process.

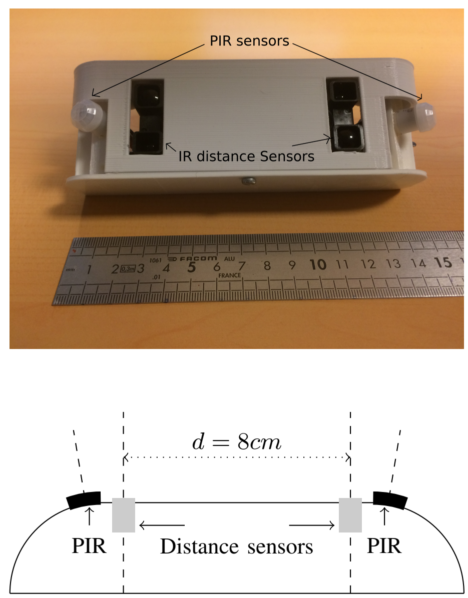

Fig. 1. Multi sensor barrier

Smart barrier solution

Our smart barrier reacts to a crossing by reporting an event with the following informations :

- quantitative : date of crossing, duration of crossing
- qualitative : direction of crossing, number of people crossing
- a reliability index (in $[0, 1]$) for the previous information

together with its identification in the system.

This event is produced by processing the signal of the distance sensors to remove noise, and then analyzing it with the help of the signals of the PIRs if necessary.

The figure above 2 shows a 22 seconds sample of thresholded data of the distance sensors of the smart barrier. Narrow peaks are residual noise that will be removed based on their width and lack of correlation with the other sensor. Five crossing of the barrier can be detected from the remaining peaks. This information is confirmed or not by similar shifts in the curves of the presence sensors.

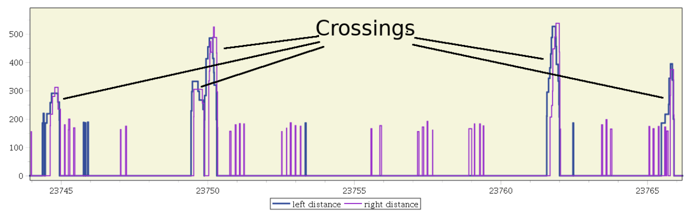

Fig. 2. Distance sensors filtered data corresponding to 5 crossings

Direction and nature of crossing can be inferred from the time shift of the curves of the distance sensors also confirmed by the PIRs.

The figures 3, 5 and 6 show different examples of crossing. On these figures the left PIR signal appears in red, the left distance sensor signal in purple, the right ones in two shades of blue. Time unit is second. PIRs signals are scaled to be visible where hole of small width are noise.

In figure 3 the blue peak starts a little bit after the purple one. That shows a crossing from right to left, that is also obvious from the PIRs signals.

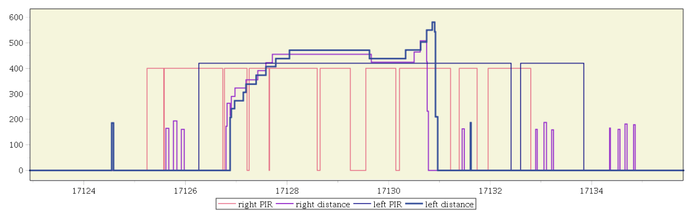

Fig. 3. Crossing from right to left

From a formal point of view, most of the signals corresponding to a single crossing have (after processing) the shape depicted in figure 4.

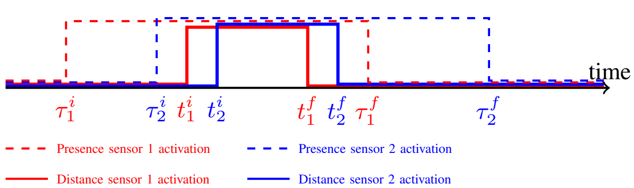

Fig. 4. Theoretical sensor activations

Speed of displacement is given by the quantity

$$S = \frac{1}{2}\left(\frac{t_2^i - t_1^i}{d} + \frac{t_2^f - t_1^f}{d}\right)$$

where d is a parameter of the barrier giving the distance between distance sensors, t^i and t^f stands for initial an final pic time. The quantity

$$L = \frac{1}{2}((t_2^f - t_2^i) + (t_1^f - t_1^i))S$$

gives the width of the person crossing the barrier. A large L may correspond to a big person, a person with for example a trolley or an armchair or to a group of several persons walking together. That can be decided from the context. Currently, our processing system take this two quantities into account when generating an event to compute the index of reliability. For example, a crossing speed too small or too large produces a poor index of reliability.

A few signals do not have the shape depicted in figure 4. This is namely what happens when several people, walking closely in the same or in different direction are crossing the smart barrier.

In figure 5 the blue peak starts before the purple one but ends after it. It is the signal we are getting when someone crosses from left to right and almost simultaneously another people crosses from right to left.

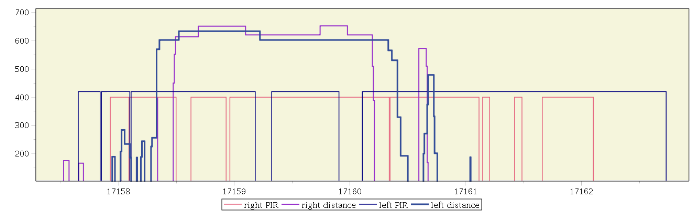

Fig. 5. Two persons crossing in front of the barrier

In figure 6 there is two very close purple peaks, but only one blue peak that starts before the start of the first purple and ends after the end of the second purple. This is a typical signal of two people crossing from left to right very closely.

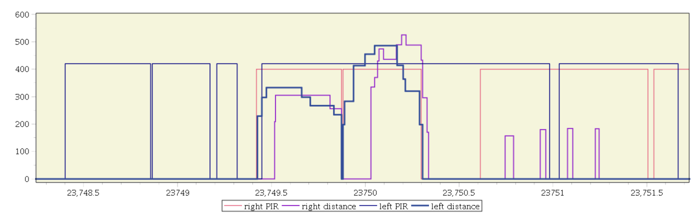

Fig. 6. Two close persons crossing in from left to right

Based on the experimentation of the barrier done is the lab, we have developed good pattern recognition skills for the different crossing and have implemented it as a signal analysis that gives correct result in more than 90 percent of the tested cases.

III. Analysis of Activities

Algorithms of activity analysis are taking as input, lists of events produced by the systems of smart barriers and are returning several scenarios of displacements of people. Two kinds of algorithms have been investigated,

1) in the first case, we are not interested in making distinction between people, and we only target to quantify the occupation of each zone (see ongoing experiment A Section IV).
2) in the other case, we would like to get activity information on some particular people, or group of people (see on going experiment B Section IV).

From an ethical view point 1) does not lead to ethical issues as individual behaviour are not identified, while 2) is clearly more problematic. Its advantage is that activity is monitored with a high granularity using sparse data that cannot be used for a more detailed analysis (at the opposite of video approaches) even if recorded, while providing information that was claimed essential for the medical community. The two installed experiments have been well accepted both by the end-users and the medical staff, most probably because of their very low intrusiveness. Still we undoubtedly monitor the overall behaviour of elderly however in accordance with French laws.

Simulator of displacements

Experiments described in the next section provides a lot of data. However, for ethical and legal reasons, we are not able to record on a large period the effective displacements and activities of people in the monitored area. Hence, we can neither compare results in terms of activities computed by our algorithm with the real displacements and activities or check the correctness of our algorithms with these data only.

Therefore we have implemented a displacements simulator for testing our algorithms.

The simulator randomly generates displacements of people and calculates the corresponding barrier events, given a topology of the monitored area, in terms of zones and of location of barriers and the number of persons in the area. Walking speeds and actual dimensions of the area are taken into account to precisely generates the events even if a fixed value is attributed to the index of reliability. A graphical visualisation of the monitored area and its occupancy with people is shown on figure 7.

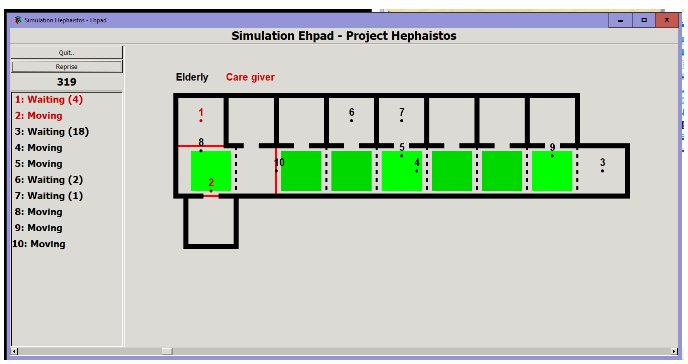

Fig. 7. Graphical interface of the simulator

Algorithm for quantitative analysis

Quantitative analysis of the event list defines a function that gives, at any instant, the number of occupancy for each zone as a list of intervals.

Initialization data of the algorithm includes a description of the connection graph of the zones of the monitored area. Each zone is a vertex, and there is an edge between two vertices, if one can move directly between the two corresponding zones without entering any other zone. In this case, by design of the monitoring system, there is a smart barrier between the two zones, and the corresponding edge is labelled by the reference of the barrier, together with its positive direction of crossing. Other initialization data expresses the occupancy constraints for each zone (for example maximum occupancy of a room, or maximum delay of occupancy of the toilets,…). Number of occupancy at the initial time for each zone is also an entry of the algorithm and is given as a list of integer intervals.

Analysis algorithm simply scrolls the list of events and for each of them :

- updates the number of occupancy for the two zones concerned by the event
- checks for this two zones that the occupancy constraints are not violated, otherwise
  - returns a warning,
  - scrolls back to the last previous event with a poor index of reliability
  - offers to replace this event by another "equivalent" - i.e. that could have been produced by the same sensor signal
  - restarts scrolling

Output is a list of successive timestamped list of number of occupancy for each zone.

Algorithm for qualitative analysis

Qualitative analysis is used when each - or at least some - people is unique for the system, and when we are interested in monitoring individual activities for these people. More precisely, we consider from one hand categories of people for which a group tracking is sufficient and from an other hand some individuals. As people are not recognized individually by our barriers, we have several possibilities at each event and considering each of them leads to an exponential growth of the set of possible scenarios. To tackle with that, qualitative analysis algorithm assumes that total number of individually monitored people is quite small, and that number of occupancy (or displacement) constraints is large - namely it expresses that some rooms are private rooms, that walking speed differs between people, that some interactions between people are scheduled…) We also introduce a rating procedure to somehow reflects the probability of our interpretation of each event in terms on individual tracking. Its simplest version only take into account different average speed of walking of people, and times between events.

As in the previous algorithm, initialization data includes a description of the connection graph of the zones of the monitored area, and a formal representation of this extended occupancy constraints. Initialization data also describes the set of monitored people (individually tracked, or tracked by groups) and provides the initial occupancy status for each zone: a list of the individually tracked people in the zone, and a number of occupancy for each group. Expected output of the analysis of a list of events is a function that gives, at any instant this occupancy status of the monitored area.

During the process, the algorithm manages a tree of possible scenarios, where each level correspond to an event date, and each node to a compatible occupancy status. A rating between 0 and 1 is associated to each branch. Root of this tree is the initial occupancy status, with the rating 1.

Structure of qualitative analysis algorithm is quite similar to the previous one, algorithm scrolls chronologically the list of events and for each of them:

- updates the tree of possible scenarios, i.e. for each branch in the tree,
  - considers the current occupancy status (the leaf one)
  - computes the compatible updated occupancy status, together with the rating for each of them,
  - extends the branch by turning the leaf into a node, defines a new leaf for each of the updates,
  - computes the rating of the newly created branches, as a product of the rating of the previous branch, by the rating of the new leaf,
- checks for this two zones that the extended occupancy constraints are not violated, and cut the branches where they are,

- if the number of branches is superior to a maximum, cuts the branches with the lower ratings.

At the end of the process, the scenario corresponding to the branch with the better rating is returned by the algorithm.

Both algorithms have been prototyped and tested against data and scenarii generated by the simulator. It turns out that the quality of the result for the qualitative analysis is very sensitive to the way we are taking into account the external information we have on the people monitored, i.e the definitions of what we called the extended occupancy constraints and the rating process.

IV. On going experiments and preliminary results

Smart barriers monitoring systems have been installed and are currently producing data in two real-life locations. The first one has been installed late 2016 in EHPAD Valrose in Nice, France, a medicalized retirement home for elderly. It is individual monitoring oriented towards residents. The second one has been set up fall 2017 at the Institut Claude Pompidou in Nice, France, in a day-care consultation center for memory deceases. It is flow monitoring oriented.

A. Monitoring at EHPAD Valrose

The monitoring area consists of a corridor that serves 6 rooms, 4 staff offices, an equipment room, toilet facilities. Six residents, their visitors and a tenth of staff members are subject to be in this area. The different groups (staff, residents, visitors) are not homogeneous in terms of gait ability. Therefore, the interest will be focused on residents tracking characterized by a slow gait speed, or the use of rollator or a wheel chair. The final objective of this experiment is to provide an estimation of the activity of the resident and to spot possible decline.

Ten smart barriers together with eleven presence detectors have been installed according to the plan displayed Figure 8. They are connected to phidget interface kits connected to a low-consumption fit-PC.

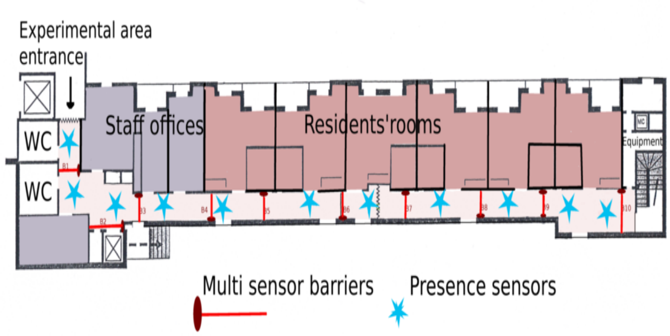

Fig. 8. EHPAD experimental area

The fit-PC proceed to a pre-filtering of the data to remove part of the noise and hence reduce the quantity of data to transfer. Data are written to text files, transferred everyday to our lab where they are later processed and analysed.

An important point to notice is the relatively small amount of people interacting in the experimental area. Their activity are mostly concentrated on time intervals: in the morning (for room cleaning and morning care of residents), during lunch time (most residents go to collective restaurant), and during diner time (residents may either be served in their rooms or go to the collective restaurant). In the afternoon the activity is more sparse.

The following table displays the number of events recorded during a full week.

Monday	Thusday	Wednesday	Thursday	Friday	Saturday	Sunday
2220	1905	1782	2353	1944	1317	1220

TABLE I
Number of recorded events

Figure 9 shows the events distribution during the day. The first figure displays this distribution a week day, while the second figure displays this distribution for a Sunday. One can notice a highest activity during week days, when medical routine is more important.

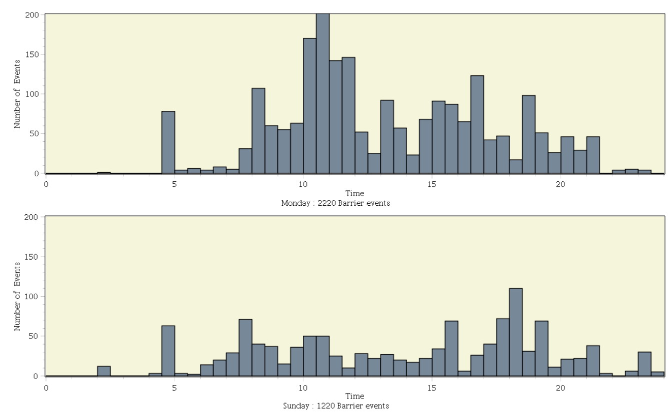

Fig. 9. Barrier events repartition. Week day and a Sunday

These data still suffer from too much uncertainties. Table II below displays the proportion of events for which the direction is not determined. We expect that a more careful calibration of the pretreatment of the data will produce a drastic decrease of these cases, which will lead to a large improvement of the algorithm.

Monday	Thusday	Wednesday	Thursday	Friday	Saturday	Sunday
12.9%	11.9%	12.4%	12.7%	14.4%	12.7%	14.1%

TABLE II
Proportion of undetermined event direction

B. Monitoring at Institut Claude Pompidou

The monitored part of the institut is presented on figure 10. It encompasses several areas : doctors and psychologists offices, consulting and evaluation rooms, waiting area, nurses offices and a staff rest room.

The area is much larger than the one of the first experiment, and we have installed 11 smart barriers to detect crossing in the corridors, 7 barriers (with only 2 distance sensors) to detect the entrance in some rooms, and 3 IR barriers in the waiting room. In this building the corridors are much larger than the corridor in the first experiment and in our lab and the distance sensor we used were not sufficient to cover the distance. Hence we used an additional pair of PIR sensors with a window to reduce the angle of detection.

Compared to the first experiment, the area is much larger and more people are implied : a medical staff of approximatively 15 persons, 6 researchers, 2 administrative staffs and a high number of visiting patients.

The objective in that experiment is slightly different since we are interested is monitoring the flow of people between the different areas.

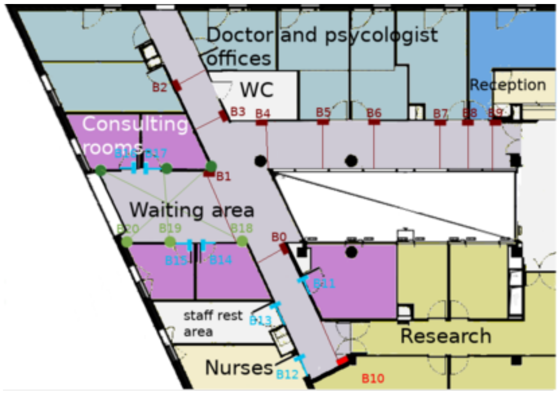

Fig. 10. Institute Claude Pompidou experimental area

V. Conclusion and perspectives

We have presented in this paper an ongoing activity of our lab concerning the use on non-intrusive monitoring systems for activity analysis that is very promising as a service for the care of frail and elderly persons at home or in public structures.

The two main contributions are

- a technical development of a smart barrier that is able to monitor its crossing and to deliver qualitative information on this crossing in terms of events
- algorithms for analyzing such lists of events and return probable scenario of activities for the set of people monitored:
  - one quantitative oriented toward occupancy of zones without individual concern,
  - one more complex, oriented toward individual tracking of some person inside a group of people.

Results section is a bit pre-matured as we faced a lot of administrative first and technical unexpected troubles while installing, configuring, and setting-up our experimental devices. We expect to be able to consolidate our data soon and to present interesting analysis results.

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